Numerical Tool for MOS Calculation with Different Mechanical/ Thermal Loads and Safety Factors Combinations

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Abstract: *For aerospace vehicles, such as rockets and satellites that are subjected to high mechanical and thermal loading, it is necessary to better understand how the structure is influenced by these loads. Because reducing the mass of the structure while maintaining strength is a very important requirement, field-tested components will be subject to different SFs (safety factors) than those that are only subjected to FEA (Finite Element Analysis). Also to further reduce the magnitude of the load factors in the MOS (Margin of Safety) calculation, mechanical loads are considered to have a different safety factor than the thermal loads. This paper proposes a solution, a tool developed to calculate MOS for structural parts for different safety factors on mechanical and thermal loads, based on data obtained from FEA. The tool takes as input the results from the NASTRAN result files and creates one excel file with MOS for each component requested by the user and different types of summary.*

Key Words: *Space Structures, Safety Factor, Load Combination, Thermal, Mechanical, NASTRAN, Python, Metallic Materials, Composite Materials*

1. INTRODUCTION

Considering the following scenario, i.e. a space vehicle (rocket, satellite, space shuttle, etc.) returning to earth from its orbit, we can find that it will be subjected to high heat fluxes on the outer skin, during the atmospheric re-entry. Although the exterior surface is made out of a TPS (Thermal Protection System) to resist these conditions, high temperatures will appear on some parts of the internal structure made out of metallic or composite materials. As an example, the IXV (Intermediate eXperimental Vehicle) atmospheric re-entry demonstrator, developed within the FLPP (Future Launcher Preparatory Program) and funded by ESA, reported max temperatures of 1400 K on the outer skin, and 400 K on some parts of the internal structure, when the re-entry speed reached about 28 Mach [1]. The IXV mission which flew on 11 February 2015 provided valuable information on the displacements and temperatures in the structure thanks to the sensors and environment data collection instruments implemented for the flight mission.

During a mission, the space vehicle can encounter a number of mechanical and thermal loads, which can be generated by operational events or environmental conditions. The design process consists of making system implementation decisions to meet certain goals in the presence of uncertainty. The goals are usually weight reduction, increased payload capacity, reliability, strength, etc. Also, the design needs to satisfy the structural requirements described by the positive MOS values obtained for buckling, crippling, fracture control, fatigue, etc. analyses [5].

To account for uncertainties a structural part has been designed historically to support a load considerably larger than the maximum expected applied load. This load is established when the maximum expected applied load is multiplied by a FOS (Factor Of Safety). At the beginning there were differences between the definition used for design load, expected load and applied loads. The U.S. Army/Air Corps has established consistent definitions which are still used today in the aerospace industry and which are presented in the table below [6].

Table 1. Terminology Definitions [6]

Limit Load	The maximum load expected on the structure during its service life including ground handling, transport to and from orbit including abort conditions, and on-orbit operations
Ultimate Load	Product of the Limit Load times the Ultimate Factor of Safety. The maximum load that a structure should withstand without incurring rupture or collapse. Must be less than Allowable Ultimate Load
Yield Load	Product of the Limit Load times the Yield Factor of Safety. The maximum load that a structure should withstand without exceeding the yield stress of the material. Must be less than Allowable Yield Load
Allowable Ultimate Load	An allowable load based on ultimate criteria is the maximum load at which structural failure will not occur (the structure should withstand three seconds).
Allowable Yield Load	An allowable load based on yield criteria is the maximum load at which structural yielding will not occur.

The limit load defined above is generally used for aircraft structures and components. The performance requirements for a commercial or military aircraft are provided by the certifying authority in each country. For the space industry, definitions are slightly different, as environments in spacecraft applications are difficult to characterize. The limit load in this case is defined as the maximum anticipated load that stresses a structure during a loading event, mission or load regime. Factors associated with uncertainty in the model are usually reported in the limit load. This uncertainty is accounted by adding a factor in the early design load stages. The factor accounts for the immaturity of the solution and for changes in launch vehicle and forcing functions. Engineering practices call for a minimum factor of 1.5 for the preliminary load cycle, then, as the structure is refined, the load factor is reduced. The application of uncertainty factors has been taken over for the first time from the unmanned spacecraft flight practice, but this has the disadvantage that it adds initial mass to the structure, a mass that may be difficult to remove in future design cycles. It is easier to add mass to components in specific areas than to remove mass from them [5]. The FOS is used not to cover all uncertainty but to lower the chance of failure given all the variables. As engineering practices and tools have evolved, the value of FOS has decreased over the years. The lowest FOS commonly used in the space industry to show analytically that the structure will not break or fail (ultimate FOS) is 1.25 in value. MIL-HDBK-340 [10] and DOD-HDBK-343 [11] specify this value for unmanned space shuttle missions when combined with a static qualification test to 1.25 times the limit load. Manned space shuttle programs use an FOS of minimum 1.4 because human safety is at risk. For yield factors of safety, common values range between 1.0 and 1.25, so that the structure is not permanently deformed enough to jeopardize the mission [7].

The FOS for ultimate and yield loads are defined as:

$$\mathrm{FOS_{ultimate}} = \frac{\text{Ultimate Load}}{\text{Limit Load}} \tag{1}$$

$$\mathrm{FOS_{yield}} = \frac{\text{Yield Load}}{\text{Limit Load}} \tag{2}$$

During the design process a higher FOS for ultimate formulation is used than for the yield. This is in accordance with the material strength properties and it is better for the design. Yielding is a concern for space vehicles because permanent deformations can occur during the launch stage and can prevent the booster from separating. Even a small deformation in a latch or hinge can prevent a mechanism to deploy. Despite these potential effects, in most cases it would be conservative to use the same FOS for yield and ultimate, because even if a critical component yields, the mission can continue. The spacecraft will have relatively few areas where yielding is of concern and they will be investigated properly [7]. There are different values for safety factors based on multiple conditions: type of material (metallic or composite materials), verification approach level of the parts by conducting numerical analyses or experimental tests, component qualification for failure design loads, including ultimate and yield loads, type of loading, etc. [2].

An example of FOS for different materials according to ECSS standards, for space vehicles, are noted in the table below [2].

Table 2. FOS for Space Vehicles and Components

Description	Vehicle	FOS Requirements			
		FOSY	FOSU	FOSY verification only by analysis	FOSU verification only by analysis
Metallic Parts	Satellite	1.1	1.25	1.25	2.0
	Launch Vehicle	1.1	1.25	(*)	2.0
	Man-Rated Spacecraft Launch into Orbit	1.25 1.1	1.4 1.5	(*)	(*)

FRP Parts	Satellite	N/A	1.25	N/A	2.0
	Launch Vehicle	N/A	1.25	N/A	2.0
	Man-Rated Spacecraft Launch into Orbit	N/A	1.5 2.0	N/A	(*)
Sandwich parts: - face wrinkling - intracellular buckling - honeycomb shear	Satellite	N/A	1.25	N/A	2.0
	Launch Vehicle	N/A	1.25	N/A	2.0
	Man-Rated Spacecraft Launch into Orbit	N/A	1.4	N/A	(*)
Glass and ceramic structural parts	Satellite	N/A	2.5	N/A	5.0
	Launch Vehicle	N/A	(*)	N/A	(*)
	Man-Rated Spacecraft Launch into Orbit	N/A	3	N/A	(*)
(*) No commonly agreed value within the space community, usually this value is established at the beginning of the project in the technical requirements document					

To assess a structures strength for all planned and reasonably likely events, all applicable loads must be combined.

There are a number of load types that affect a space vehicle, including: acoustics, random vibrations, mechanical loads including ground operations, dynamic loads, on-orbit events, operational loads, pressure loads and thermal effects. The most important of these are the mechanical and thermal loads, especially for a re-entry vehicle.

Thermal loads on a structure may be sustained or intermittent. For sustained thermal loads, the response of the structure is one of continuous relaxation. Hence, as far as stress is concerned, a low FOS on short term yield should be adequate. It is a general engineering consensus that ideally an FOS=1.0 is enough for thermal loads. However, most engineers use a value of 1.5 for the FOS, as a conservative measure [3].

For mechanical loads the FOS ultimately depends on the material of the part, or the type of structural element. Its value ranges from 1.1 for the Yield Factor of Safety for a metallic component to a value of 3.0 for a ceramic component or 2.5 for Aluminum Honeycombs in the case of composite sandwich materials [2].

In the aerospace industry there is an additional term used, namely MOS. The design load is related to the allowable load through the MOS [4].

$$\mathrm{MOS_{yield}} = \frac{\text{Allowable Yield Load}}{\mathrm{FOS_{yield}} \cdot \text{Limit Load}} - 1 \tag{3}$$

$$\mathrm{MOS_{ultimate}} = \frac{\text{Allowable Ultimate Load}}{\mathrm{FOS_{ultimate}} \cdot \text{Limit Load}} - 1 \tag{4}$$

The MOS can be summed up as a measure of the remaining load-carrying capability of a structure under an applied load condition. The MOS value sign represents an indication whether the structure will be able to withstand the applied loads. The magnitude of this value also indicates the amount with which the applied loads can be increased without surpassing the yield or ultimate capacity of the structure. Since the relation between load and stress is linear, most of the MOS definitions are based on the stress values [5].

$$\mathrm{MOS} = \frac{\text{Allowable Stress}}{\mathrm{FOS} \cdot \text{Calculated Stress}} - 1 \tag{5}$$

Calculated stress is the stress obtained using numerical methods such as finite element method (FEM) for certain applied boundary conditions. Different type of load conditions such as mechanical, thermal, pressure, etc. loads are considered in the FE analyses. Failure criteria in calculated stress could be: maximum shear stress, maximum Von Mises stress, principal stress, etc., depending of the failure scenario that is agreed upon before the analysis. When dealing with multiaxial loading conditions, the Von Mises stress is usually preferred and commonly used by engineers [5].

2. LOAD COMBINATION METHOD

Due to mass budget requirements, constraints and to prevent the excessive loading which is directly leading to an increase in the mass of the spacecraft, it is necessary to assess lower design limit loads without jeopardizing the integrity and reliability of the structure. To address this need a solution is to apply different safety factors to mechanical and thermal loads. This paper proposes a numerical tool that uses the superposition principle to combine thermal and mechanical loads with different FOS to accurately obtain MOS for different parts of a space vehicle.

The proposed method uses the FEA results and subsequently computes them with the developed tool using different safety factors. The simulation has to be run for different loads, mechanical and thermal, then the results combined for each element included in the FEM model to calculate the MOS based on the FOS specified for that element.

A space vehicle structure is designed and built with metallic and composite materials; in this paper ceramic or special ablative materials are not taken into consideration. In some parts of the flight, tri-axial stress conditions are produced and it is necessary to determine if any yielding will occur under such combined stresses action. Test results indicate that the yield strength in ductile materials is accurately defined by strain energy of distortion theory, also known as the equivalent stress theory [8]. The Von Mises stress or equivalent tensile stress is defined as the uniaxial tensile stress that would generate the same distortion energy as is created by the actual combined applied stresses. Under multiaxial loading conditions, the general formulation for the Von Mises stress can be written as:

$$\sigma_{VM} = \sqrt{\frac{1}{2} \cdot \left((\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} + \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6 \cdot ({\sigma_{12}}^2 + {\sigma_{23}}^2 + {\sigma_{31}}^2) \right)} \tag{6}$$

A ductile material is said to start yielding when the von Mises stress reaches a value known as the yielding strength of the material, this is known as the von Mises yield criterion and is applied on metallic materials as a first failure condition. The maximum value for the von Mises stress is retrieved from the FEA results and used as the applied stress, in this case the MOS (Eq. 5) becomes:

$$MOS = \frac{\sigma_{allowable}}{FOS \cdot \sigma_{VMmax}} - 1 \tag{7}$$

Because of the linearity of the FE method, the stress values from an analysis case with thermal and mechanical loads can be divided into 2 subcases, one subcase containing only the mechanical loads and the other only the thermal loads. The final result of combining the stress from different subcases will equal the result of having all the loads in the same subcase.

This method applies only for linear static cases where the element stresses can be algebraically summed up for different loads. In case of material, geometric or other nonlinearity this method would be invalid.

$$\sigma_{mechanical+thermal} = \sigma_{mechanical} + \sigma_{thermal} \tag{8}$$

Inserting the general formulation for the von Mises stress into the margin of safety equation and considering the stress divided into mechanical and thermal components, a general equation for a margin of safety, with different safety factors, is obtained:

$$MOS = \frac{\sigma_{allowable}}{\sqrt{\frac{1}{2} \cdot \begin{pmatrix} \left(FOS_m \cdot (\sigma_{1m} - \sigma_{2m}) + FOS_t \cdot (\sigma_{1t} - \sigma_{2t})\right)^2 + \\ \left(FOS_m \cdot (\sigma_{1m} - \sigma_{2m}) + FOS_t \cdot (\sigma_{1t} - \sigma_{2t})\right)^2 + \\ \left(FOS_m \cdot (\sigma_{1m} - \sigma_{2m}) + FOS_t \cdot (\sigma_{1t} - \sigma_{2t})\right)^2 + \\ 6 \cdot \begin{pmatrix} (FOS_m \cdot \sigma_{12m} + FOS_t \cdot \sigma_{12t})^2 + \\ (FOS_m \cdot \sigma_{23m} + FOS_t \cdot \sigma_{23t})^2 + \\ (FOS_m \cdot \sigma_{31m} + FOS_t \cdot \sigma_{31t})^2 \end{pmatrix} \end{pmatrix}}} - \tag{9}$$

where:

$\sigma_{allowable}$	- Yield or ultimate stress from material characteristics,
FOS_m	- Factor of Safety for mechanical loads,
FOS_t	- Factor of Safety for thermal loads,
$\sigma_{1m,2m,3m}$	- Stress obtained from mechanical loads,
$\sigma_{1t,2t,3t}$	- Stress obtained from thermal loads.

The above equation allows to calculate the margin of safety for the FEM elements that have different safety factors applied to thermal and mechanical stress results.

This formulation applies for the SOLID elements in the FE model such as HEXA, TETRA, etc. as defined in NASTRAN [9]. For the SHELL formulation the von Mises equation simplifies:

$$\sigma_{VM} = \sqrt{\sigma_{11}^2 - \sigma_{11} \cdot \sigma_{22} + \sigma_{22}^2 + 3 \cdot \sigma_{12}{}^2} \tag{9'}$$

When inserting the above equation in the MOS formula with the same procedure, the equation becomes:

$$MOS = \frac{\sigma_{allowable}}{\sqrt{\begin{matrix}(FOS_m \cdot \sigma_{1m} + FOS_t \cdot \sigma_{1t})^2 + (FOS_m \cdot \sigma_{2m} + FOS_t \cdot \sigma_{2t})^2 - \\ (FOS_m \cdot \sigma_{1m} + FOS_t \cdot \sigma_{1t}) \cdot (FOS_m \cdot \sigma_{2m} + FOS_t \cdot \sigma_{2t}) + \\ 3 \cdot (FOS_m \cdot \sigma_{12m} + FOS_t \cdot \sigma_{12t})^2\end{matrix}}} - 1 \tag{10}$$

Up to now the MOS equations presented apply to metallic materials with the von Mises stress used as the calculated stress, but this method can be used for any user-defined MOS formulation. In case of composite materials the same principle can be applied on the calculation of the MOS for HC (Honeycomb Composite) shear strength. The most important measured properties for HC panels are bare strength compressive strength, crush strength and L direction and W direction plate shear strength [12]. The equation for the MOS of a HC panel shear strength is:

$$MOS = \frac{1}{FOS \cdot \sqrt{\left(\frac{\sigma_{13}}{FsL}\right)^2 + \left(\frac{\sigma_{23}}{FsW}\right)^2}} - 1 \tag{11}$$

where:

σ_{13} - Shear stress in 13 plane, XZ global,
σ_{23} - Shear stress in 23 plane, YZ global,
FsL - Shear strength of the sandwich panel in L direction, X global,
FsM - Shear strength of the sandwich panel in W direction, Y global.

Breaking the shear stress, σ_{13} and σ_{23}, into stress obtained from thermal and mechanical loads, and inserting the FOS under the root symbol, we obtain the following equation.

$$MOS = \frac{1}{\sqrt{\left(\frac{FOS_m \cdot \sigma_{13m} + FOS_t \cdot \sigma_{13t}}{FsL}\right)^2 + \left(\frac{FOS_m \cdot \sigma_{23m} + FOS_t \cdot \sigma_{23t}}{FsW}\right)^2}} - 1 \tag{12}$$

These are some examples of MOS equations with separated thermal and mechanical stress results and different FOS that have been implemented in the numerical tool presented in the next chapter.

3. SOFTWARE TOOL FOR LOAD RESULTS COMBINATION

A software tool was developed as a necessity for a European space project. The purpose of this tool was to solve the problem of investigating the cold structure (internal structure) of a space vehicle during its mission, including launch, flight in orbit, de-orbit, atmospheric re-entry and landing. This tool proved to be valuable in offering information with regards to the MOS for different components and where failures occurred. It provided a quick way to post-process results obtained from FE analysis with NASTRAN especially considering the high number of cases for which the structure was analyzed.

Considering the worst case scenario, during re-entry, the vehicle is subjected to high temperatures and pressures. To slow down the vehicle, a number of parachutes are deployed which insert high mechanical loads into the structure. Because of the strict mass requirements the strength to weight ratio must be optimized. Some of the structural parts are validated through experimental test campaigns; because of this the FOS applied in the MOS calculations are different than the ones applied for the parts that will only be numerically analyzed. Also the margins of safety are calculated considering that mechanical and thermal loads have different FOS applied to them.

The software tool was developed using the Python language version 3.6.4. A SQL database was used to store and manipulate data extracted from result files obtained from NASTRAN.

A GUI (Graphical User Interface) was developed with PyQt library and Qt Designer software to enhance the user experience. A flowchart of the software operations is presented below.

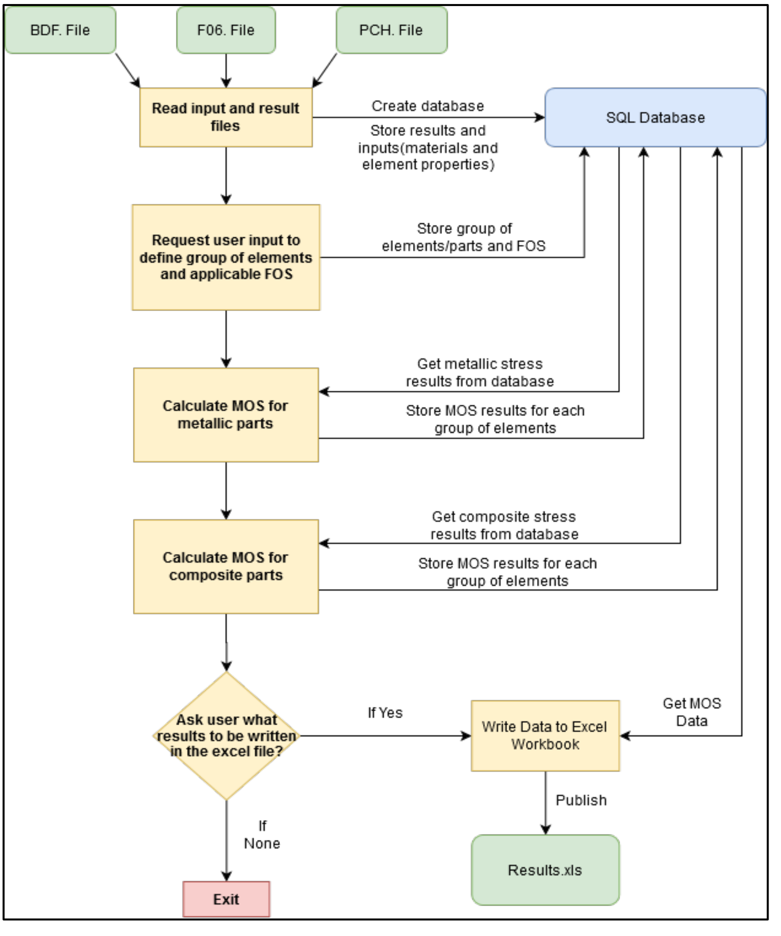

Figure 1. Numerical Tool Flowchart

The first step of the algorithm is to read the input files. The user provides the location and name of the bdf. file, which is the input file for the NASTRAN [9] solver, that contains details about all the materials and element properties, the f06. file which contains the results for the Strength Ratio values for composite materials and the pch. file which has all the data about stress and forces on each element type from the analysis.

The software reads the files line by line and stores all the required information in an SQL database.

In the second step, the user provides information with regards to the element groups that represent specific parts in the FE model.

The user also specifies the FOS to be used for each material, part and also type of load (mechanical or thermal). These values are stored in the SQL database.

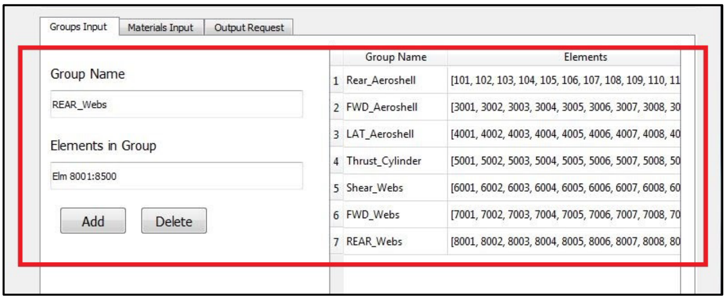

Figure 2. Element group input by user in GUI

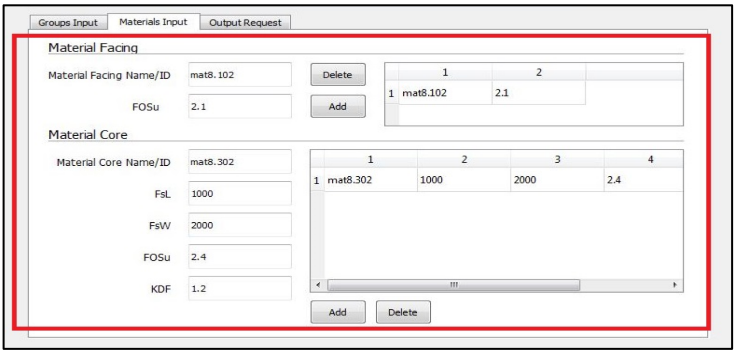

Figure 3. Material properties and FOS input by user in GUI

In the next two steps the algorithm calls the SQL database for the required data to calculate the MOS for the metallic components and the composite materials. The results are stored then again in the database.

For each user specified element group the tool will calculate the MOS for each element based on the type of material, property and specified FOS for that element.

In the last two steps the tool creates and publishes an excel file, at the request of the user, with MOS for each element and also a summary with the minimum MOS for each group. An example can be seen in figure X containing the summary table for the MOS calculation for HC Shear Strength.

For each element group name the results show the element id (EID) from the FE model, the ply id (PID) of the composite material in this case the ply id of the core, the values for shear stress in XZ and YZ directions obtained from mechanical and thermal loads separately, the HC admissible in the L and W direction (FsL and FsW), the mechanical FOS specified by the user and the minimum calculated MOS.

Group Name	EID	PID	Shear XZ Mechanical [Pa]	Shear YZ Mechanical [Pa]	Shear XZ Thermal [Pa]	Shear YZ Thermal [Pa]	FsL [Pa]	FsW [Pa]	Subcase	FOS HC	MOS HC
Thrust_Cylinder	610387	17	-168296.2	-96034.02	-129428.3	-33956.9	2040000	1190000	1	2.4	1.91
Shear_Webs	620705	7	103863.5	26160.22	156743	42360.31	2040000	1190000	1	2.4	3.59
REAR_Aeroshells	405614	7	-218.2523	-247501.5	2797.365	130298.5	2040000	1190000	1	2.4	1.57
FWD_Aeroshells	505990	6	114675.4	-364826.2	-38667.15	87962.68	1190000	680000	1	2.4	-0.15
Vertical_Panels	341192	0	796418	-366806.3	-227207.2	67773.5	1330000	760000	1	1.5	0.04
Parachute_Bay_Floor	360148	0	793281.7	8278.354	-110572.8	863.7197	1330000	760000	1	1.5	0.23
Parachute_Bay_Walls	367515	2	-12131.81	17305.88	-7433.651	52013.42	1330000	760000	1	1.5	8.58
Parachute_Bay_Panels	367127	7	-693.3744	-11271.07	-526.7189	-4914.98	1330000	760000	1	1.5	33.80
Front_Bulkhead	250850	7	5511.362	-32648.69	104441.6	-519154	2040000	1190000	1	1.5	1.08
Parachute_Bulkhead	201381	7	57278.8	-29612.32	568824.5	-437116	2040000	1190000	1	1.5	0.94
Middle_Bulkhead	150222	7	-1238347	155122.1	36596.14	-10446.5	2040000	1190000	1	1.5	0.10

Figure 4. Excel table results from the Numerical Tool

As a note, the tool can handle multiple mechanical subcases/loads but can only handle one thermal case. The FE analysis must be set so that the mechanical loads are put in independent cases from the thermal loads and the last case of the analysis contains only temperature loads. The results file will contain the MOS calculation for the mechanical cases combined with the last thermal case which is the same through the analysis. There is also a MOS summary for each group of elements/parts based on the subcase number, so that the user can see the element with the minimum MOS for each subcase.

Thrust_Cylinder										
EID	PID	Shear XZ Mechanical [Pa]	Shear YZ Mechanical [Pa]	Shear XZ Temp [Pa]	Shear YZ Temp [Pa]	FsL [Pa]	FsW [Pa]	Subcase	FOS HC	MOS HC
610387	17	-168296.2	-96034.02	-129428.3	-33956.9	2040000	1190000	1	2.4	1.9144
611045	17	-118726.1	-26966.4	-56539.43	-11939.9	1955000	1190000	2	2.4	4.3714
610025	17	2514.426	293.8727	8708.666	8248.529	1190000	680000	3	2.4	54.311

Figure 5. MOS summary for a specific part (Thrust Cylinder)

4. NUMERICAL ANALYSIS STUDY

A numerical study was performed to verify the validity of the equations and also the software results. Let's consider a plate with a thickness of 20 mm, a length of 100 mm and a width of 25 mm, which is modeled with QUAD4 type shell elements, numbered from 1 to 10 with 18 nodes.

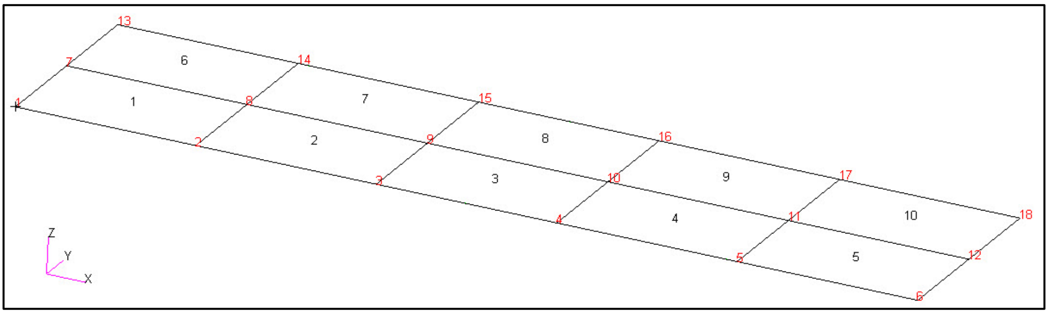

Figure 6. Plate finite element model

We consider 2 types of materials for this plate, a 7075-T7351 type aluminum and a composite honeycomb sandwich made out of a HEXCEL 1/8-5056-.001 aluminum type honeycomb and CFRP MTM44-1/M40J prepreg facings [12].

The initial reference temperature is set at 20 degrees C, also for thermal displacements the CTE is specified for each material definition at 2.35e-5 m/(m°C) for aluminum material and 6e-7 m/(m°C) for the CFRP facing. Material characteristics in NASTRAN input card format are presented below [10].

```
$ Description of Material :
$ AL7075-T7351
MAT1     101     7.1+10  2.68+10 .33     2800.   2.35-5  20.
$ CFRP MTM44-1/M40J
MAT8     135     7.868+107.868+10.03     2.85+9  4.6+9   4.6+9   1608.
+        6.-7    6.-7    20.     4.84+8  2.18+8  4.84+8  2.18+8  4.562+7
$ HEXCEL 1/8-5056-.001
MAT8     121     1000.   1000.   .25     1000.   4.826+8 1.931+8 72.
+        2.3-5   2.3-5   20.     1.+23   1.+23   1.+23   1.+23   1.+23
```

Figure 7. Material Input Card

For boundary conditions, an edge is considered to be fixed, all 6 DOF blocked, and on the other edge a vertical force of 900 N is distributed on the 3 nodes. There is also a temperature gradient applied starting from 20 degrees on the fixed edge and ending at 200 degrees on the opposite edge. We run 3 cases for each material type, one with only mechanical loading (Subcase 1), one with only thermal loading (Subcase 2) and one with both mechanical and thermal loading (Subcase 3). The safety factors for the mechanical and thermal load are considered variable, upon user consideration.

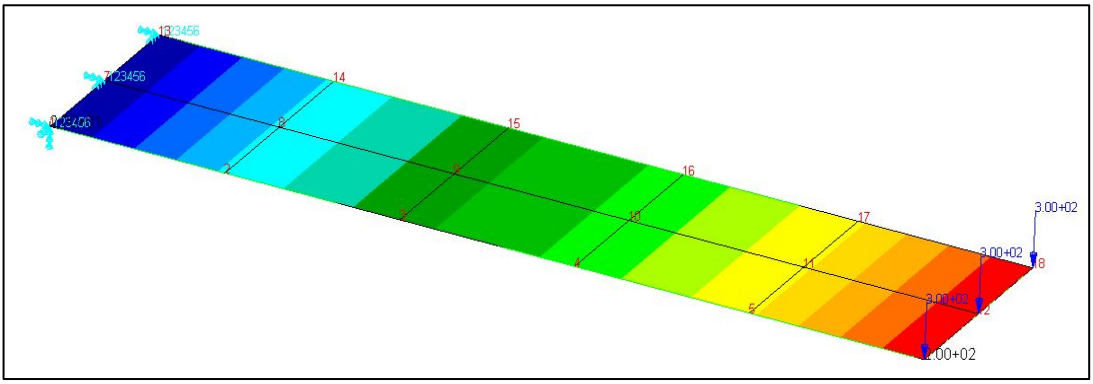

Figure 8. Boundary conditions

For the metallic configuration, the results for element 6 of the plate can be seen in the table below. As expected, superposition property of the linear FE method, mechanical stress results, subcase 1, can be summed with thermal stress results, subcase 2, to obtain the results for subcase 3, which is a combined thermal and mechanical loads case.

S T R E S S E S I N Q U A D R I L A T E R A L E L E M E N T S (Q U A D 4)					
	ELEMENT	FIBER	STRESSES IN MATERIAL COORD SYSTEM		
SUB.	ID.	DISTANCE	NORMAL-X	NORMAL-Y	SHEAR-XY
1	6	-1.000000E-02	-4.860000E+07	-7.433768E+06	1.679707E+06
2	6	-1.000000E-02	2.328306E-07	-1.321365E+06	4.081365E+06
3	6	-1.000000E-02	-4.860000E+07	-8.755132E+06	5.761071E+06

Figure 9. Stress results, f06 file

We use the results from subcases 1 and 2, mechanical and thermal, as an input for the developed software tool.

Based on the input that it gets from the user for the FOS, mechanical and thermal stress results, and the implied (Eq. 8), the tool will write the following table of results.

The tool will output the element with the smallest MOS and will provide data for each stress value so that the user can see the differences between the thermal and mechanical stress results.

EID	Sig1m [MPa]	Sig2m [MPa]	Sig12m [MPa]	Vmmech [MPa]	Sig1t [MPa]	Sig2t [MPa]	Sig12t [MPa]	Vmtemp [Mpa]	SigY [MPa]	SigU [MPa]	FOSy	FOSu	FOSt	MOSy	MOSu
6	48.6	7.433768	-1.6797	45.43571	2E-13	-1.3214	4.08137	7.191566	337.8	434.4	1.1	1.25	1.1	5.670277	6.570035

Figure 10. Results for element with minimum MOS

where:

Sig1m - Mechanical stress in direction 1, X global,

Sig2m - Mechanical stress in direction 2, Y global,

Sig12m - Mechanical shear stress 12, XY plane,

Vmmech - Mechanical Von Mises stress, (Eq. 10),
Sig1t - Thermal stress in direction 1, X global,
Sig12t - Thermal shear stress 12, XY plane,
Vmtemp - Thermal Von Mises stress, (Eq. 10),
FOSy - FOS for yield failure mechanical,
FOSu - FOS for ultimate failure mechanical,
FOSt - FOS applied to thermal loads,
MOSy - MOS computed with (Eq. 11) with yield FOS,
MOSu - MOS computed with (Eq. 11) with ultimate FOS.

The utility of this tool is that the user can specify different FOS for each desired element or part; as seen below the FOS values can be individually changed for each element from the plate model.

EID	Sig1m [MPa]	Sig2m [MPa]	Sig12m [MPa]	VM Mech [MPa]	Sig1t [MPa]	Sig2t [MPa]	Sig12t [MPa]	VM Temp [MPa]	SigY [MPa]	SigU [MPa]	FOSy	FOSu	FOSt	MOSy	MOSu
1	48.6	7.433768	1.679707	45.43571	-3E-13	-1.32137	-4.08137	7.191566	337.8	434.4	1.1	1.25	1.1	5.670277	6.570035
2	37.8	-1.28212	-0.80866	38.48259	-4.9E-13	-0.79171	0.990354	1.889234	337.8	434.4	1.2	2.1	1.1	6.247077	4.347965
3	-27	-0.1787	-0.00316	26.91109	-1.9E-13	0.355959	0.325012	0.666036	337.8	434.4	1.3	1	1	8.600623	15.02124
4	-16.2	-0.04682	0.286305	16.18423	4.66E-14	0.10106	0.208246	0.374583	337.8	434.4	1.4	1.05	1.2	13.86204	24.45447
5	5.399997	-0.12494	-0.2333	5.478464	-3.3E-13	-0.06017	-0.42126	0.732122	337.8	434.4	1.5	1.4	1.3	39.45783	54.66174
6	48.6	7.433768	-1.67971	45.43571	2.33E-13	-1.32137	4.081365	7.191566	337.8	434.4	1.7	1.3	1.4	3.348265	6.284305
7	37.8	-1.28212	0.808662	38.48259	3.96E-13	-0.79171	-0.99035	1.889234	337.8	434.4	1.05	2.5	1.1	7.270122	3.496145
8	-27	-0.1787	0.003164	26.91109	9.31E-14	0.355959	-0.32501	0.666036	337.8	434.4	1.9	2	1.1	5.580993	7.04139
9	-16.2	-0.04682	-0.2863	16.18423	9.31E-14	0.10106	-0.20825	0.374583	337.8	434.4	1.8	1.6	1.1	10.56773	15.72993
10	5.399997	-0.12494	0.233304	5.478464	-9.3E-14	-0.06017	0.421261	0.732122	337.8	434.4	1	1.2	1.1	59.01149	63.6881

Figure 11. MOS summary for each element of the plate with different FOS values individually

In the case of the composite sandwich material the stress results for the core ply are presented in the figure below.

Stress is exported by NASTRAN in fiber and matrix direction. Linearity of the method is demonstrated again, the summation of stresses from subcases 1 and 2 will equal the stress in subcase 3.

```
S T R E S S E S   I N   L A Y E R E D   C O M P O S I T E   E L E M E N T S   ( Q U A D 4 )
       ELEMENT   PLY  STRESSES IN FIBER AND MATRIX DIRECTIONS    INTER-LAMINAR  STRESSES
 SUB.     ID      ID     NORMAL-1      NORMAL-2      SHEAR-12     SHEAR XZ-MAT  SHEAR YZ-MAT
  1       6        6  -5.26455E+07   4.83838E+06   1.16049E+05   -9.43114E+05  -9.34542E+02
  2       6        6   4.48719E+03  -2.45597E+04   1.33207E+04    0.0           0.0
  3       6        6  -5.26410E+07   4.81382E+06   1.29369E+05   -9.43114E+05  -9.34542E+02
```

Figure 12. Stress results for composite material, f06 file

Considering that the orthotropic material (MAT8) was used to define the properties of the material and the CTE is only present in the 1 and 2 directions, X and Y directions in global axes, the value for shear stress in out of plane directions is null for subcase 2 where only thermal loads are present.

The sandwich core will not expand in the Z global direction. The results for the HC core shear strength published by the numerical tool are presented below.

Because there is no shear stress for the core from the thermal load case, the MOS is calculated considering only the mechanical loads with the algorithm from (Eq. 13).

Group Name	EID	PID	Shear XZ Mechanical [Pa]	Shear YZ Mechanical [Pa]	Shear XZ Temp [Pa]	Shear YZ Temp [Pa]	FsL [Pa]	FsW [Pa]	Subcase	FOS HC	FOSt	MOS HC
Plate	6	6	-943114	-934.5424	0	0	2400000	1400000	1	2.45	1.1	0.038677

Figure 13. Minimum MOS element considering composite material

5. CONCLUSIONS

Aerospace structures are usually designed using the FOS approach. The practice is to impose a load case on the structure that is derived from an extreme value, the load value. The structure is designed to withstand the limit load times the FOS.

The available conventional post-processing software tools can combine the results, from the FE analysis, by multiplying them by a load factor or adding them together, but in these cases the user cannot specify certain parts or elements of the analysis to be different. Engineers can use factors of safety that apply to the loads when building the FE analysis and then calculate the MOS based on the results or they can apply FOS directly to the results when post-processing the outcomes. Our tool and method presented in this paper allow the loads to be split on different parts and also specify unique FOS for each element or part, based on materials or other conditions and requirements. MOS are automatically computed based on engineering formulations for metallic and composite materials, in the post-processing phase of the analysis.

Future research and software update will focus on implementing more MOS algorithms, especially for composite materials with CFRP facing and HC failure. The objective is to allow the user to input his own MOS equation so that he can use any desired formulation based on the available stress and material allowable. Other capability to consider is to add multiple thermal load cases and allow the user to select the preferred combination of results.

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